Proceeding of the IEEE
International Conference on Robotics and Biomimetics (ROBIO)
Shenzhen, China, December 2013

A Manipulator's Safety Control Strategy based on Fast Continuous Collision Detection

Jing Xia, Zainan Jiang, Hong Liu, Hegao Cai, Guangxin Wu, *Member, IEEE*

***Abstract*—In this paper we propose a strictly conservative and novel hybrid safety control strategy consisting of the pre-contact safety strategy and the post-contact safety strategy in order to provide safety guarantees and enable continuous motions. An optimal motion trajectory planning that limits jerk, acceleration and velocity of robot motion and can obtain a time optimal motion is introduced as post-contact safety strategy. The optimal motion trajectory planning can reduce the impact forces during occurring collision and keep high efficiency of manipulator and continuous motions. Then we describe a fast continuous collision detection as pre-contact safety strategy to avoid collision. The advantages of this method are that it can solve the tunneling problem and check the whole trajectory. Finally, the proposed hybrid safety control strategy has been implemented on a 7 degrees-of-freedom(DOF) humanoid manipulator, and the experimental results demonstrate the validity of the novel hybrid safety control strategy.**

I. Introduction

In future robots will need to work around humans and to touch them. They must be able to operate safely and reliably, otherwise, they will cause human injury or damage to their surrounding environment. So, conventional safety strategies for industrial robots can not satisfy developmental demand of robots. Safety control strategy for robots coexisted with humans or fine equipment has been gathering increasing attention from both industrial and research communities.

In this research, as the subject of our study we have chosen the safety strategy to prevent mechanical injury. In general, safety control strategies of robots can be classified as pre-contact safety strategies and post-contact safety strategies [1],[2]. Pre-contact safety strategies consider avoiding collision. Post-contact safety strategies aim to reduce potential injuries after collisions. Such as the former strategy corresponds to avoiding collision by means of collision detect system, the latter strategy to minimizing impact force by means of restricting the velocity and acceleration of robot motion.

Research supported by Research Fund for the Doctoral Program of Higher Education of China(20122302120046), National Natural Science Foundation of China (Grant No. 51305097), Fundamental Research Funds for the Central Universities(Grant No.HIT.NSRIF.201168)

Jing Xia is with State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, Heilongjiang Province，China (phone: 86-451-86402330; e-mail: 382327499@qq.com).

Zainan Jiang is with State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, Heilongjiang Province, China (corresponding author to provide phone:86-451-86402330; e-mail: jiangzainan@hit.edu.cn).

To achieve smooth motion and minimizing impact force, an optimal real-time motion trajectory planning limiting jerk, acceleration and velocity of robot motion is introduced as post-contact safety strategy in this paper. Works on real-time trajectory planning have been published [4]-[9]. Liu [4] uses seven cubics for on-line representing a smooth mono-dimensional motion. Limiting jerk in robot trajectories contributes to extended life of manipulator and more precise tracking accuracy. A good review of motion planning methods that are focused on jerk bounding can be found in [5]. In [5] Macfarlane and Croft present a jerk-bounded, near-time-optimal trajectory planner that uses quantic splines, but only for 1DOF systems. Amirabdollahian et al. [6] use a seventh order polynomial for the entire trajectory with a minimum jerk model, while Seki and Tadakuma [7] propose the use of fifth order polynomial for the entire trajectory. Kröger [8] introduces a new method for motion trajectory generation of robots with multiple degrees of freedom. The method enables robots to react instantaneously to unforeseen and unpredictable events at any time instant and in any state of motion. Herrera and Sidobre [9] propose a limiting maximum motion conditions and time optimal trajectory planner based on seven cubic equations, but the approach is not applicable in general, but only for some special cases. Therefor the trajectory planning will be supplemented in this paper.

Collision detection (CD) is a fundamental robot safety control problem. Collision detection is classified into two types. One is discrete collision detection and another is continuous collision detection. But most of the prior work on CD has focused on discrete collision detection, which check for collisions at fixed time instants only. Okada [10] develops a precise collision detection system for humanoid robots using AABB based discrete collision detection technique. In [11] authors make use of cylinders and spheres to cover a redundant manipulator, and a compact method of detecting collisions between two cylinders is introduced. The performance of the proposed scheme is demonstrated for a redundant manipulator via simulations and experiments. However it is possible to miss a collision between two successive instances ("tunneling problem"). To overcome the limitations of discrete collision detection, continuous collision detection has been developed. In [12] authors present an algorithm to perform continuous collision detection for articulated models. Täubig et al.[13] present a real-time self-collision detection algorithm based on continuous collision detection. A major challenge of continuous collision detection is modeling the continuous

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motion between the two successive positions and orientations of the object.

Most of the prior work in manipulator's safety control strategy has been limited to a single safety strategy. In order to secure robots, many types of safety control strategies are indispensable. The aim of this paper is to propose a novel hybrid safety control strategy consisting of pre-contact safety strategy and post-contact safety strategy. The novel safety control strategy will be implemented on a 7DOF humanoid manipulator (cf. Fig. 1).

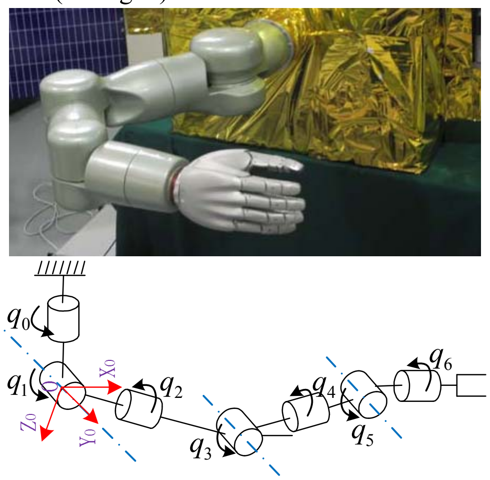

Fig. 1. 7DOF humanoid manipulator

This paper is organized as follows. Section II gives framework of the novel hybrid safety control strategy. A post-contact safety control strategy of the hybrid safety control strategy is analyzed in section III. Section IV describes a continuous collision detection as pre-contact safety control strategy. Section V presents simulation and real-world experimental results to demonstrate the validity of the novel hybrid safety control strategy.

II. FRAMEWORK OF NOVEL SAFETY CONTROL STRATEGY

In this section, we propose a framework of the novel hybrid safety control strategy. The framework is shown in Fig.2. Safety of manipulator is directly linked with the velocity and acceleration of manipulator motion. Therefore we make the first attempt to limit the impact force of the manipulator by restricting the velocity and acceleration of the manipulator motion. But overly velocity restrictive will strongly limit the performance of manipulator. The manipulator moves must under limited maximum motion conditions ($J_{\max}$, $A_{\max}$ and $V_{\max}$), in order to obtain minimum execution time for improving the efficiency of manipulator. $J_{\max}$ is the maximun jerk, $A_{\max}$ is the maximun acceleration, $V_{\max}$ is the maximun velocity. Therefore the hybrid safety control strategy of manipulator firstly introduces an optimal motion trajectory planning that limits jerk, acceleration and velocity of robot motion, and can obtain a time optimal motion. The optimal motion trajectory planning can reduce the potential injury during occurring collision and keep the high efficiency of manipulator.

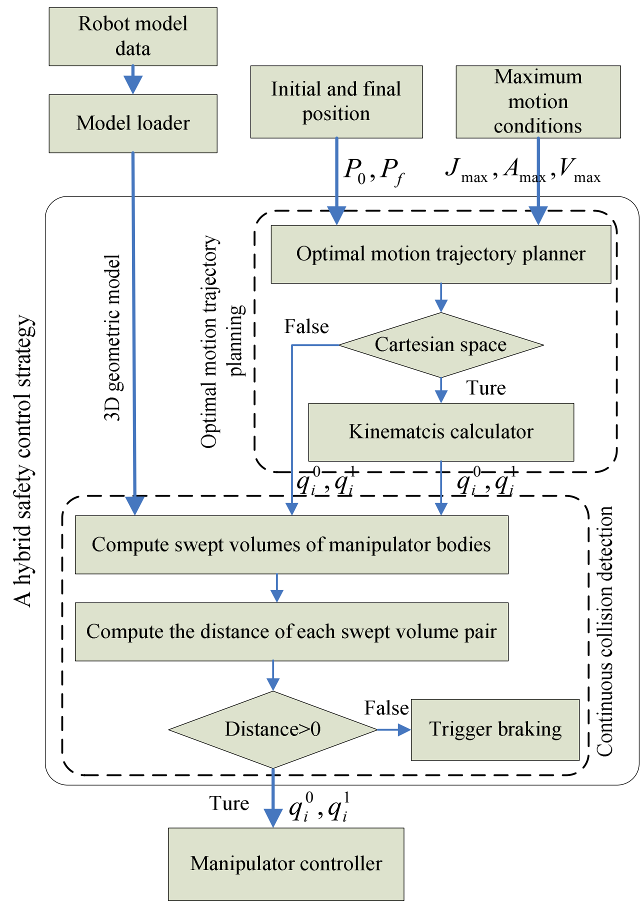

Fig. 2. A framework of novel hybrid safety control strategy

We make the second attempt to use a fast continuous collision detection of manipulator to avoid occurring collisions. Fast collision detection is a fundamental and essential function for developing of safety control strategy. Considering discrete collision detection algorithms check for interferences at fixed time instants only and tunneling problem. A continuous collision detection approach is introduced to solve the tunneling problem and check the whole trajectory. Therefore this paper will contribute a strictly conservative and precise hybrid safety control strategy.

III. OPTIMAL MOTION TRAJECTORY PLANNING

The motion trajectory planning limits jerk, acceleration and velocity in Cartesian or joint space. As the joint moves under maximum motion conditions ($J_{\max}, A_{\max}, V_{\max}$), we obtain a minimum execution time for improving the efficiency of manipulator. Considering the canonical case of the Fig.3 without lost of generality, the optimal motion can be separated in three different type sections by integration:

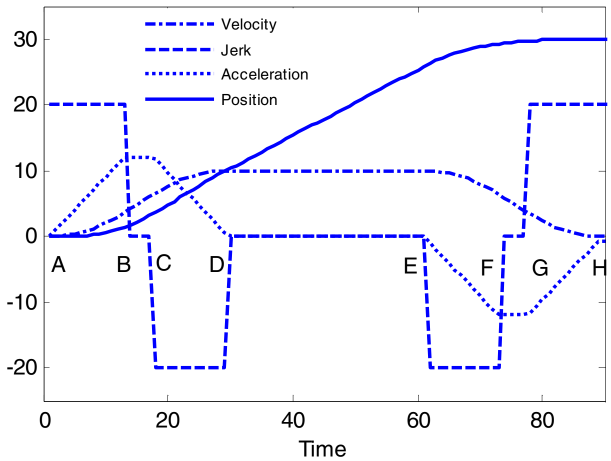

Fig. 3. Jerk, acceleration, speed and position curves of optimal motion trajectory planning

Case 1: the motion with a saturated jerk $\pm J_{\max}$ (AB, CD, EF, GH segments):

$$\begin{aligned} J(t) &= \pm J_{\max} \\ A(t) &= A_i \pm J_{\max} t \\ V(t) &= V_i + A_i t \pm \frac{1}{2} J_{\max} t^2 \\ X(t) &= X_i + V_i t + \frac{1}{2} A_i t^2 \pm \frac{1}{6} J_{\max} t^3 \end{aligned} \tag{1}$$

Case 2: the motion with a saturated acceleration $\pm A_{\max}$ (BC, FG segments):

$$\begin{aligned} J(t) &= 0 \\ A(t) &= \pm A_{\max} \\ V(t) &= V_i \pm A_{\max} t \\ X(t) &= X_i + V_i t \pm \frac{1}{2} A_{\max} t^2 \end{aligned} \tag{2}$$

Case 3: the motion with a saturated velocity $\pm V_{\max}$ (DE segment):

$$\begin{aligned} J(t) &= 0 \\ A(t) &= 0 \\ V(t) &= \pm V_{\max} \\ X(t) &= X_i \pm V_{\max} t \end{aligned} \tag{3}$$

Where $J(t)$, $A(t)$, $V(t)$, $X(t)$ represents jerk, acceleration, velocity and position functions respectively. A_i, V_i and X_i are initial conditions of i segments.

In this case, initial and final kinematic conditions are null. The motion trajectory can be separated in four different particular cases according to whether or not maximum acceleration or maximum speed is reached (cf.Fig.4). Three boundary conditions are obtained.

1) Case 1: $V_{\max}$ is reached and $A_{\max}$ is reached , $T_v \geq 0$ and $T_a \geq 0$. T_v is saturated velocity time, T_a is saturated acceleration time.
2) Case 2: $V_{\max}$ is unreached and $A_{\max}$ is reached and , $T_v = 0$, $T_a \geq 0$.
3) Case 3: $A_{\max}$ is unreached and $V_{\max}$ is unreached , $T_a = T_v = 0$, $T_j \geq 0$. T_j is saturated jerk time.
4) Case 4: $V_{\max}$ is reached and $A_{\max}$ is unreached , $T_v \geq 0$ and $T_a = 0$.

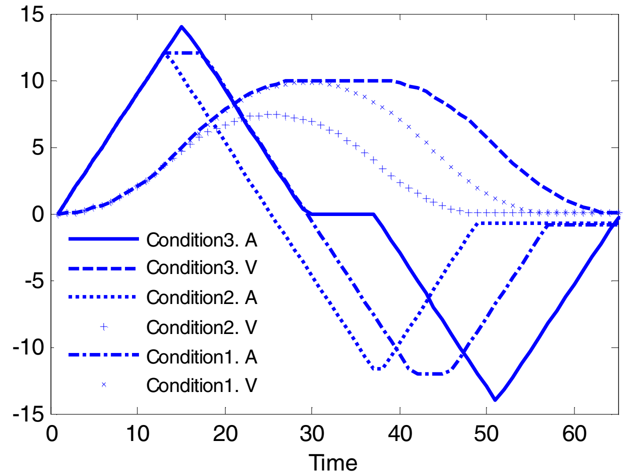

Fig. 4. Three boundary conditions

Considering boundary conditions, the pseudocode of the motion trajectory planning is shown in Fig.5. Different trajectory cases depend on the distance between an initial position and a final position and the kinematic-motion constraints. When the optimal motion trajectory planning is used in Cartesian space of manipulator, the relation between manipulator joint velocities and Cartesian velocities is given by:

$$\dot{\theta} = Jac^{-1}(\theta)[V \quad \Omega]^T \tag{4}$$

Where V and Ω represent the linear and angular velocities of the robot's end effector and Jac is the jacobian matrix. The linear velocities V and Ω can be directly obtained by the optimal motion trajectory planner.

Begin

Calculate distance D and $T_a = \frac{V_{\max}}{A_{\max}} - \frac{A_{\max}}{J_{\max}}$

If $T_a \geq 0$

Calculate boundary conditions $D_{thr1} = \frac{A_{\max} V_{\max}}{J_{\max}} + \frac{V_{\max}^2}{A_{\max}}$

Calculate boundary conditions $D_{thr2} = 2\frac{A_{\max}^3}{J_{\max}^2}$

If $D \geq D_{thr1}$ then

$T_j = \frac{A_{\max}}{J_{\max}}$ $\quad T_a = \frac{V_{\max}}{A_{\max}} - \frac{A_{\max}}{J_{\max}}$ $\quad T_v = \frac{D - D_{thr1}}{V_{\max}}$

Calculate motion trajectory $X(t)$ (Eq 1,2,3)

If $D \geq D_{thr2}$ then

$T_j = \frac{A_{\max}}{J_{\max}}$ $\quad T_a = \sqrt{\frac{A_{\max}^2}{4J_{\max}} + \frac{D}{A_{\max}}} - \frac{3A_{\max}}{2J_{\max}}$ $\quad T_v = 0$

Calculate motion trajectory $X(t)$ (Eq 1,2)

Else

$T_j = \sqrt[3]{\frac{D}{2J_{\max}}}$ $\quad T_a = 0$ $\quad T_v = 0$

Calculate motion trajectory $X(t)$ (Eq 1)

If $T_a < 0$

Calculate boundary conditions $D_{thr3} = 2\sqrt{\frac{V_{\max}^3}{J_{\max}}}$

If $D \geq D_{thr3}$ then

$$T_j = \sqrt{\frac{V_{\max}}{J_{\max}}} \quad T_a = 0 \quad T_v = \frac{D - D_{thr3}}{V_{\max}}$$

Calculate motion trajectory $X(t)$ (Eq 1,3)

Else

$$T_j = \sqrt[3]{\frac{D}{2J_{\max}}} \quad T_a = 0 \quad T_v = 0$$

Calculate motion trajectory $X(t)$ (Eq 1)

End

Fig.5. Pseudocode of optimal motion trajectory planning

IV. . FAST CONTINUOUS COLLISION DETECTION

A. Swept volume compute

In the research, manipulator bodies and swept volumes are represented by sphere swept convex hulls (SSCH). The SSCH enclosing a link is precomputed using the approach contained all points from the CAD model in the lowest possible volume. Sphere swept convex hulls of a finite set of points $P = \{[p_l]_{l=1}^n\}$ are defined as

$$V(r;P) = convP + \{b \in R^3 \mid |b| \geq r\} \tag{5}$$

where $convP$ is the convex hull of a point-set P. So each volume is the Minkowski-sum of a convex polyhedron given by a set of points and a ball of radius r.

A revolute joint provides single axis rotation. Revolute joint angle come from the previous optimal trajectory planning, it is bounded by joint intervals $[\alpha_0, \alpha_1]$, and $|\alpha_1 - \alpha_0| < \pi$. Every point of manipulator model moves on a circular arc within angle α_0 and α_1 around revolute axis. The circular arc is contained in a SSCH, the SSCH bounding is obtained by using two points and a radio (cf. Fig.6), and is defined as

$$Circ(\alpha_0, \alpha_1, (r; [p_l]_{l=1}^n)) = V(r + f \max|p_l|; \\ [p_l^0 + fp_l^{1/2}, p_l^1 + fp_l^{1/2}]_{l=1}^n) \tag{6}$$

With

$$\phi = \frac{\alpha_1 - \alpha_0}{2}, f = \frac{1 - \cos\phi}{2}, p_l^{1/2} = T(\alpha_0 + \phi) p_l$$

Where $T(\alpha_0 + \phi)$ is transition matrix of the revolute joint.

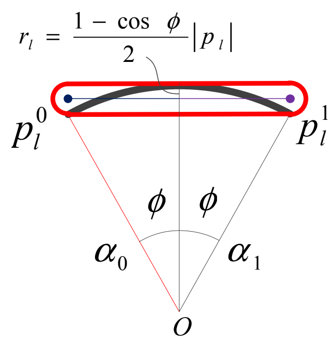

Fig.6. Bounds of a circular arc by SSCH

For a articulated structure consisting of several revolute joints, the motion trajectory of these points is no longer circular arc, the effect of different joints must be taken into account in this case. For example, a manipulator consists of two links, the configuration of joint 1 is bounded by $[\alpha_0, \alpha_1]$, and Joint 2 is bounded by $[\alpha_2, \alpha_3]$ at the same time. Every point of the joint1 moves on a circular arc, but the actual motion trajectory of the joint 2 is not known. We will approximate the actual motion trajectory by assuming that manipulator's links move separately according to priority order. The approximate process of the actual trajectory can be separated in two different cases:

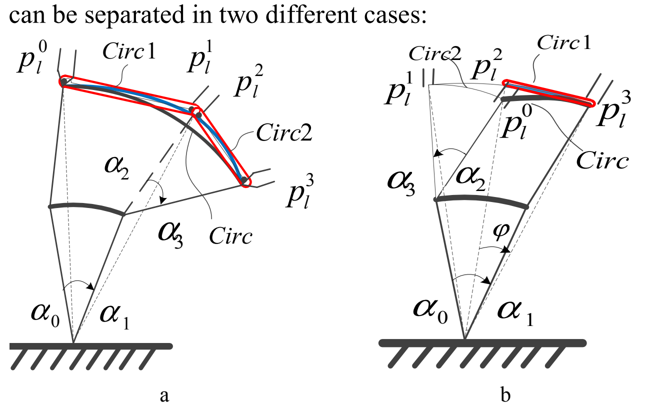

Fig.7. Approximate process of several joints actual trajectory

Case1 is shown in Fig.7a. We can obtain the actual motion trajectory of the joint 2.

$$Circ \subset Circ1(\alpha_0, \alpha_1, (r; [p_l]_{l=1}^n)) + Circ2(\alpha_2, \alpha_3, (r; [p_l]_{l=1}^n) \tag{7}$$

The tight bound of circular arc Circ1 and Circ2 is obtained by using (6), formally:

$$Circ1(\alpha_0, \alpha_1, (r; [p_l]_{l=1}^n)) = V1(r_1; [p_l^0, p_l^1]_{l=1}^n) \tag{8}$$

$$Circ2(\alpha_2, \alpha_3, (r; [p_l]_{l=1}^n)) = V2(r_2; [p_l^2, p_l^3]_{l=1}^n) \tag{9}$$

Thus

$$Circ \subset V1(r_1; [p_l^0, p_l^1]_{l=1}^n) + V2(r_2; [p_l^2, p_l^3]_{l=1}^n) \\ \subset V(\max(r_1, r_2); [p_l^0, p_l^1, p_l^2, p_l^3]_{l=1}^n) \tag{10}$$

Case2 is shown in Fig.7b. The actual motion trajectory is obtained by

$$Circ \subset Circ1(\varphi, (r; [p_l]_{l=1}^n)) \\ = V(r_3; [p_l^2, p_l^3]) \tag{11}$$

Because joint intervals are small, this approximation is strictly conservative.

B. Fast collision detection

A GJK-algorithm is introduced as collision detection block of the safety control strategy for computing the distance between a pair of convex polyhedra given as arrays of points. The GJK algorithm can easily be adopted to SSCHs. The distance of swept volume is given by the distance of convex polyhedra pair given as arrays of points minus both extension radii.

$$dis(V(r_i;p_i),V(r_J;p_J)) = GJK_r(r_i;p_i;r_j;p_j) = GJK(p_i;p_j) - r_i - r_j \quad (12)$$

Manipulator's braking is triggered and stops whole manipulator's motion when collisions are detected, namely any of the distance of the SSCH pair is zero.

V. EXPERIMENT

A. Experimental Platform

The hybrid safety control strategy was implemented on a teleoperation system of humanoid manipulator. Figure 8 shows the structure of the teleoperation system. It consists of two sides: operator and remote robot, which are connected through local area network (LAN). Communication time is fixed to 50ms. At the operator side, a high-fidelity virtual

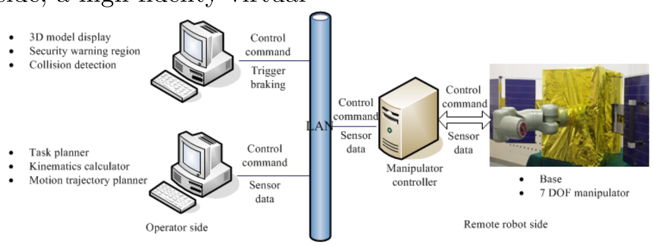

Figure 8 Structure of humanoid manipulator teleoperation system

model of the remote robot and environment is created for the predictive display and collision detection by software vc 6.0 and open inventor. Optimal motion trajectory planning, swept volumes compute and fast collision detection are carried out on the operator side. The remote robot side consists of a 7DOF humanoid manipulator with non-offset S-R-S configuration [14]. The humanoid manipulator is constructed by modular joints. The manipulator has be equipped with various sensors that supply manipulator control schemes in teleoperation. Manipulator controller is used for controlling the real manipulator system and communicating with the operator side.

B. Experimental results

The optimal motion trajectory planning was used in joint space of manipulator in experiments. Fig.9 and Fig.10 respectively denote the curves in jerk, acceleration, velocity of second and fourth joint motion when there is no collision. The motion trajectory of the second joint belongs in case 4, whereas, the fourth joint belongs in case 1.

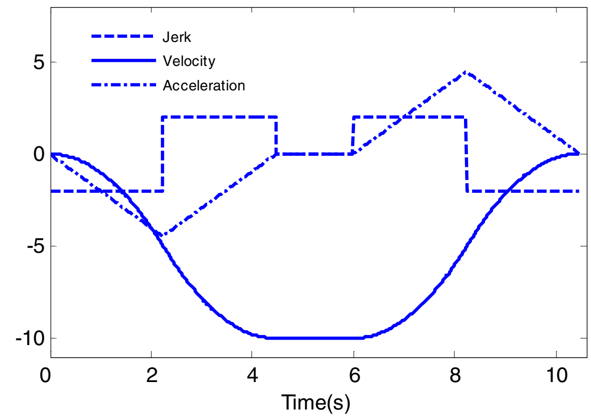

Fig.9. Jerk, acceleration, velocity curves of the second joint($J_{max} = 2^\circ/s^3, A_{max} = 5^\circ/s^2, V_{max} = 10^\circ/s$)

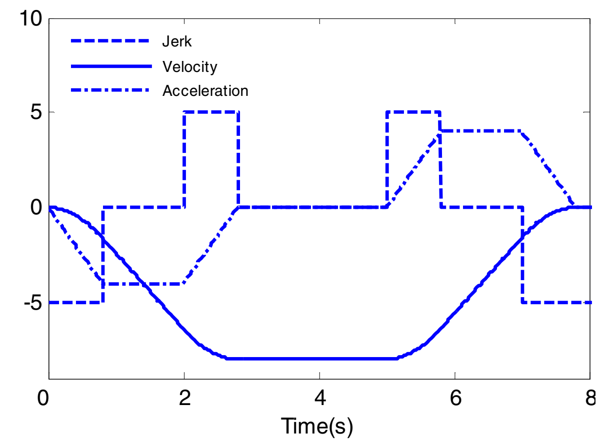

Fig.10. Jerk, acceleration, velocity curves of the fourth joint($J_{max} = 5^\circ/s^3, A_{max} = 4^\circ/s^2, V_{max} = 8^\circ/s$)

Fig.11 illustrates the simulate process of the experiment. Solid model describes the current movement state of the humanoid manipulator. Ware frame model describes the future movement state of the humanoid manipulator. Then the swept volumes of all bodies and the distances between swept volumes and obstacle are computed. The most possible collision points are given by GJK-algorithm. The braking is triggered when the swept volumes of the manipulator and obstacle occur collision in virtual environment, manipulator stops motion.

Computation time for the continuous collision detection is shown in Fig.12. Computational time for detecting collisions is constant (0.05ms) when there is no collision. However it takes more computation time and becomes 0.11 ms in the worst case. The experimental results demonstrate the safety and efficiency of the novel hybrid safety control strategy.

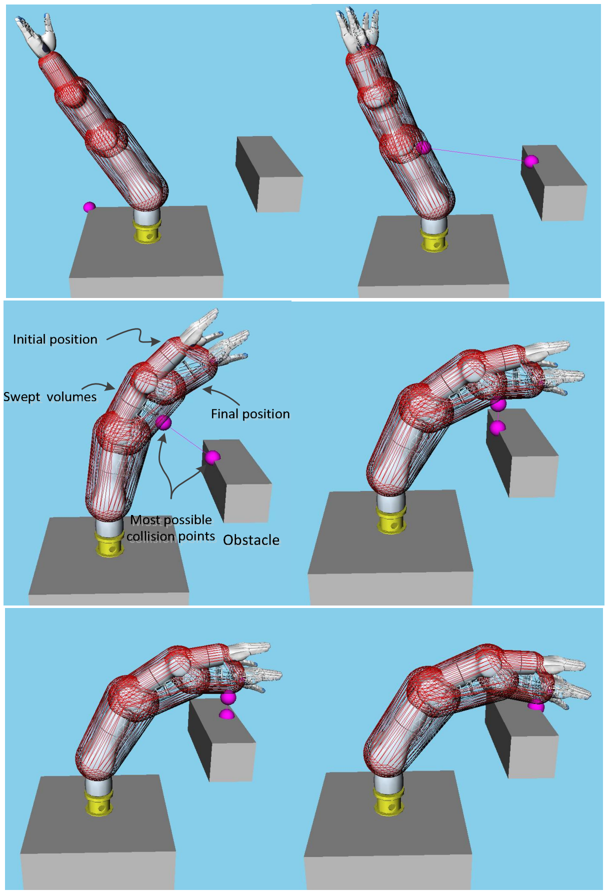

Fig.11. Simulate process of novel safety control strategy experiment

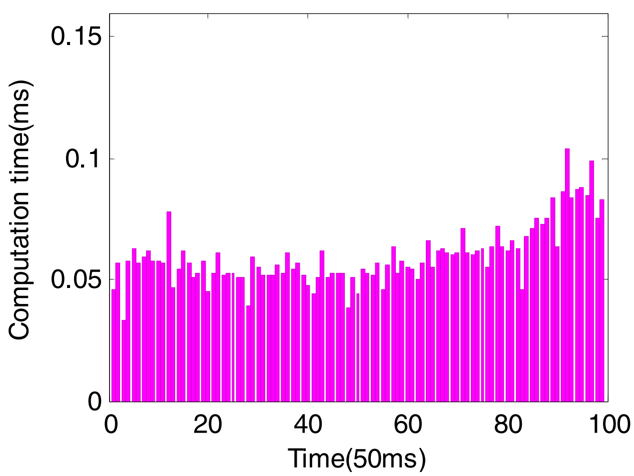

Fig. 12. Computation time of continuous collision detection

VI. Conclusion

The prior soft motion trajectory planning algorithm was incomplete, our first contribution is that case4 was discussed and the motion trajectory planning algorithm was supplemented. The optimal motion trajectory planning can perform well to generate globally optimal trajectory in environments without collision and limit maximum motion conditions of robot.

Our second contribution is that a fast continuous collision detection is introduced in the safety control strategy to solve the limitations of discrete collision detection. The effect of several revolute joints on swept wept volume compute has been discussed in this paper.

Last but not least, we have presented a novel hybrid safety control strategy which comprises optimal motion trajectory planning and fast continuous collision detection. According to the results of our experiments, the novel hybrid safety control strategy is able to assure smooth collision free movement on the manipulator robot in real time interaction.

References

[1] J. Heinzmann, A. Zelinsky, "Quantitative safety guarantees for physical human-robot interaction," *The International Journal of Robotics*, vol.22, no.7-8, pp.479–504, July 2003.

[2] K. Ikuta, H.Ishii, M. Nokata, "Safety evaluation method of design and control for human-care robots," *The International Journal of Robotics*, vol.22, no.5, pp.281–297,May 2003

[3] Y. Yamada, " Evaluation of human pain tolerance and its application to designing safety robot mechanism for human–robot coexistence,"*Journal on Robotics and Mechatronics*, vol.9, no.1, pp.65–70, 1997.

[4] S.Liu, "An on-line reference-trajectory generator for smooth motion of impulse-controlled industrial manipulators," in *Proc.7th International Workshop on Advanced Motion Control,* Maribor, 2002, pp. 365–370.

[5] S.Macfarlane, E.A. Croft, "Jerk-bounded manipulator trajectory planning: design for real-time applications," *IEEE Transactions on Robotics and Automation*, vol.19, no.1, pp.42–52, Feb.2003.

[6] F.Amirabdollahian, R. Loureiro, W. Harwin, "Minimum jerk trajectory control for rehabilitation and haptic applications," in *IEEE international conference on robotics and automation*, St. Paul, 2002, pp. 3380–3385.

[7] K. Seki,S.Tadakuma, "Minimum jerk control of power assiting robot based on human arm behavior characteristic," in *International Conference on Systems*, Hague, 2004, pp. 722–727.

[8] T.Kröger, F.M.Wahl, "Online trajectory generation: basic concepts for instantaneous reactions to unforeseen events," *IEEE Transactions on Robotics*, vol.26, no.1, pp.94–111, Feb.2010.

[9] I. Herrera, D. Sidobre,"On-line trajectory planning of robot manipulator's end effector in cartesian space using quaternions," in *Proc.15th International Symposium on Measurement and Control in Robotics*, 2005.

[10] K. Okada, M. Inaba, H.Inoue, "Real-time and precise self collision detection system for humanoid robots," in *Proceedings of international Conference on Robotics and Automation*, Barcelona, 2005, pp.1072–1077.

[11] R.Patel, F.Shadpey, F.Ranjbaran, J.Angeles, "A Collision Avoidance Scheme for Redundant Manipulators: Theory and Experiments. Journal of Robotic Systems," *Journal of Robotic Systems,* vol.22, no.12, pp.737–757, Dec.2005.

[12] R.Stephane, J. K.Young., C. L.Ming, M. Dinesh, "Fast continuous collision detection for articulated models," in *Proceedings of the ninth ACM symposium on Solid modeling and applications*,2004, pp.145–156.

[13] H.Täubig, B.Bäuml, U.Frese, "Real-time swept volume and distance computation for self collision detection," in *Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems* , San Francisco,2011,pp.1585–1592.

[14] X.J.Huo, Y.W. Liu, L.Jiang , H.Liu, "Design and development of a 7-DOF humanoid arm." in *IEEE International conference on robotics and biomimetics*, Guangzhou,2012, pp.277–282.